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Flexible attachment designs for rapid tooling: A contribution to greater design freedom within pin-type moulding, spatially curved CFRP panels

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Abstract

Form flexible moulding by pin-type tooling enables the mass-customised production of spatially curved panels. As the design freedom of such panels is limited to the arrangement density of pins, more compactly arranged pins come to mind. However, increasing this density is limited since the increase in the number of pins and thereby also the mould costs is disproportionately large. To manufacture panels with filigree geometries while using lower pin arrangement densities, attaching rapid tooling moulds is useful. Since such moulds are to be attached on uneven interpolation surfaces, novel flexible and non-destructive (dis-)attachment designs of rapid tooling attachments were developed and investigated. The results enable greater design freedom within pin-type moulding, spatially curved panels.

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1. Introduction

Considering the current trends for energy saving by using lightweight design, carbon fibre reinforced plastics (CFRP) present a possible solution. A study by Lässig et al. expressed the importance of this topic: Accordingly, it is expected that the demand for CFRP components by 2020 will increase 17% per year, but, in the same period the processing costs need to be reduced by 40% [1]. Furthermore, mass customisation [2] in the CFRP component market should be considered for the future, if this has not yet been integrated.

To produce individual, spatially curved CFRP components in a mass customised way, form-flexible moulds are advantageous. E.g., the interface between the avalanche shovel made of CFRP and its shovel handle shown in Fig. 1 can be manufactured specifically for the individual shovel handle without changing the mould due to its form-flexibility. Furthermore, different spatially curved CFRP panels for lightweight design of, e.g., chassis in automotive and aircraft manufacturing or shipbuilding can be manufactured on the same yet geometry-flexible mould. As a result, each CFRP no longer needs a rigid mould, specific to its geometry [3].

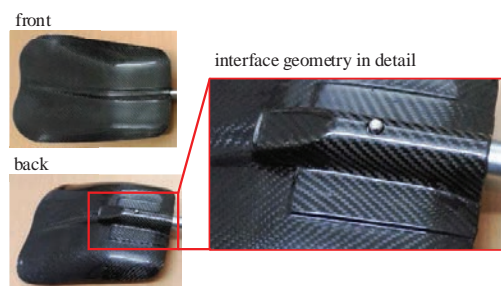


Fig. 1. Avalanche shovel, an example of a CFRP component with need for specific interface geometry due to attaching individual shovel handle.

Thus, the mould costs can be distributed across all single panel geometries which are produced with one flexible mould. Consequently, the panel costs decrease¹. To do this, pin-type tooling is useful. In this process, the mould is composed of an array of independently adjustable pins. The resulting free-form but discrete surface can be smoothed by applying an elastic interpolation layer (IPL). [3]

¹ Assuming a sufficiently high number of single panels each with different geometries are produced on a given mould.

2. Designing pin-type moulds with thinner and more compactly arranged pins for increasing the design freedom within CFRP is limited

But, as indicated in Fig. 2, the design freedom within the CFRP panel depends on the pin's size: the larger the pins, the fewer pins must be produced, assembled, maintained, and adjusted by actuators and thus the machine complexity decreases, but the creative flexibility with regard to the design elements that can be mapped within the CFRP panel is restricted.

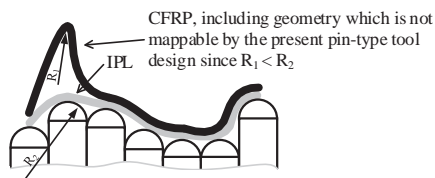


Fig. 2. The pin size limits the design freedom within CFRP panels.

As the design representation accuracy and thus the corresponding manufacturability of such panels is limited by the arrangement density of pins, thinner and more compactly arranged pins are an intuitive solution. However, an increase in arrangement compactness leads to a disproportionately large increase in costs due to the multifold increase in the number of required pins associated with increasing density. E.g. considering a moulding square represented by p^2 pins, halving of pin thickness for doubling number of pins within the same moulding square, increases the number of pins by four times. Therefore, designing pin-type moulds with thinner and more compact arranged pins to increase the design freedom within CFRP is limited.

3. Additive manufactured miniature attachments extend manufacturing limits of pin-type moulds

An alternative approach is assembling miniature attachments on the elastic IPL as introduced in [3]; this is useful in order to be able to manufacture such needed filigree designed panels while still using pin-type moulds with small pin densities. Fig. 3 illustrates an example of miniature attachment geometries, which make possible, e.g., a diameter within the CFRP component that is smaller than the diameter given by the pins (a), an undercut (b), and a nearly right angle (c) for moulding, but retain the pin size and number of the present pin-type mould. The entire CFRP manufacturing process can look like this: firstly, adjusting the existing pin-type mould as near as possible to the CFRP geometry (1/3); secondly, building and placing the corresponding miniature attachment(s) on the IPL (2/3); and thirdly, laminating the CFRP on the shape which is now mapped by the surface of the IPL, including the miniature attachments placed on the IPL (3/3).

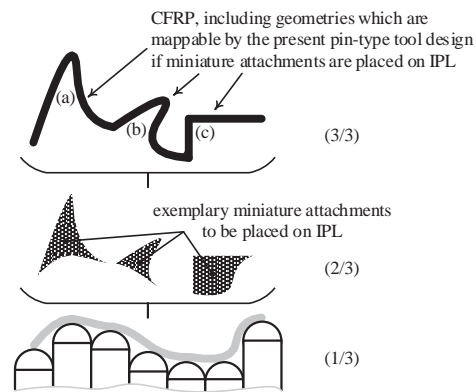


Fig. 3. Extending manufacturing limits of already available pin-type moulds by assembling miniature attachments on the IPL.

Thus, the manufacturability and the corresponding design freedom in developing such CFRP panels are extended. Additive manufactured rapid tooling [4,5] moulds can be quickly and inexpensively produced in almost any geometry and are therefore particularly appropriate as miniature attachments (MA) for CFRP laminating.

4. Need for action to address (dis)assembling additive manufactured miniature attachments on spatially curved and dimpled interpolation layers

However, such miniature attachments must fulfil several conditions, which are usual characteristics of pin-type moulds, in order to be attached. The IPL may be uneven after the pin adjustment due to mapping the spatially curved CFRP panels. Furthermore, the IPL may have dimples spread on its entire surface which is due to firmly fixing the IPL on the pins. This can happen, e.g., by applying a vacuum under the IPL but within the space or vacuum chamber where the pins are placed (see Fig. 4) or other types of fixing which result from different kinds of fasteners. In addition, the capacity for non-destructive (dis)assembling is required since the same IPL may be used for subsequent different panel geometries.

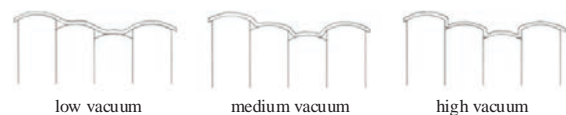


Fig. 4. The stronger the pins are attached to the IPL (here via an assumed vacuum) the stronger the IPL is dimpled.

Therefore, new flexible and non-destructive disassembly-enabled attachment designs of additive manufactured MA are needed. The next sections of this paper will explore steps to meet this need. Firstly, flexible attachment designs are developed in chapter 5, which are then compared to each other in chapter 6.

5. Flexible attachment designs

To meet the need defined in section 4, several design concepts were developed. The design idea is based on using attachment modules, each being assembled from the bottom of the MA in an assembly space, which is a material section within the MA². Fig. 5 shows attachment modules that were manufactured within this work, which are described in detail in the following.



Fig. 5. Developed and manufactured attachment modules (demonstrators).

5.1. Design concept 1: Based on the suction principle

By generating a negative pressure, e.g., by a suction cup, a connection to the IPL is achievable. The holding force is determined by the pressure difference between the pressure of surrounding air and the pressure of the air trapped in the suction volume, multiplied by the effective contact area between the suction cup and the surface [6]. Thus, the holding force is enhanced by an increase in pressure difference and an increased effective area. The higher level of surrounding pressure presses the suction module and consequently the attached MA against the IPL. If a bellows suction pad is used, higher lifting movements are possible [6], which contribute to an increase in vacuum or pressure difference and thus increases the holding force. The developed design which implements this suction principle is illustrated by Fig. 6.

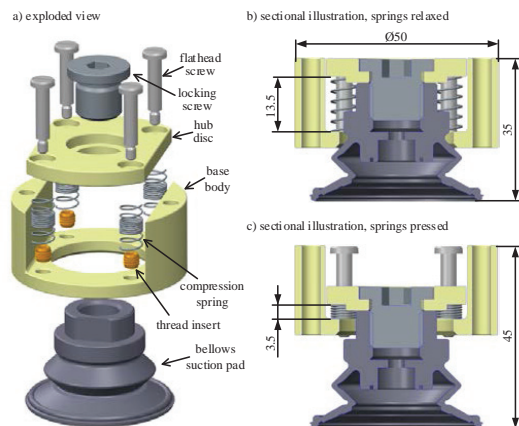


Fig. 6. Flexible attaching module based on the suction principle (with demonstrator's nominal dimensions in mm)

² See Fig. 10b and there the material section defined by the nominal dimensions Ø 51 mm & 35 mm.

Since the bellows suction pad is wrinkled as well as made of an elastic plastic, the uneven and dimpled IPL surface can be compensated. Furthermore, the disassembly occurs non-destructively due to cancelling the sealing effect. The module is placed on the IPL. By pressing down the locking screw, the bellows suction pad as well as the compression ring via the hub disc gets compressed. Thus, excess amounts of air within the suction volume are expelled out until the air sealing lips of the bellows suction pad seal up the suction chamber. After releasing the locking screw from the pressing force, the compression springs spring back until the hub disc hits the head of the locking screw. Thus, in the same manner as in the adhesion gripper described by Monkmann et al. in [6], the trapped air expands due to the increase in volume which is why the absolute pressure within the suction chamber decreases.

5.2. Design concept 2: Spreading needles angular into IPL

In handling food goods or textile technologies, needle grippers are used that drive needles into the component for picking it up, to transport it, etc. [7,8]. Transferring this concept into an application for compensating an uneven and dimpled IPL results in, e.g., the design illustrated by Fig. 7.

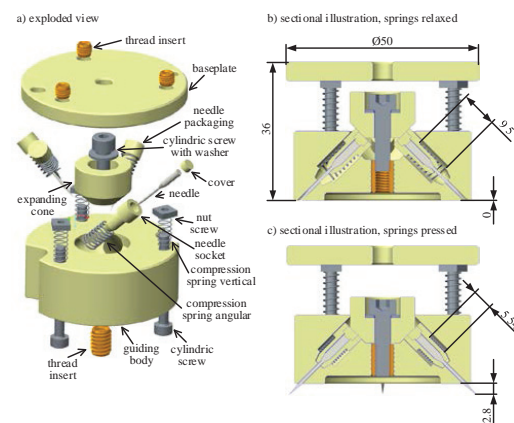


Fig. 7. Flexible attaching module based on spreading needles angular into IPL (with demonstrator's nominal dimensions in mm).

Screwing lowers the expanding cone. Thus, the needle packages move outwards in the arranged angle via the contact with the cover. The length of the extension depends on the intended penetration depth. Thus, spatially curved and dimpled surfaces can be compensated to a limited extent since each needle is able to prick³ with a different depth into the IPL, due to the different distances of the needles from the IPL. Unscrewing results in retracting the needles back into the

³ As the experimental procedure in chapter 6 shows, the pricking generated a negligible material cut within the IPL that is not problematic even after removal of needles: after application of another spatially curved shape, the elastic material of the IPL elongates and thus contracts transversally which results in closing the gap.

guiding body by the angular compression springs whereby it is disassembled. The sharp needles prick into the IPL but do not completely puncture through it, in order to prevent a vacuum leakage within the IPL in case a vacuum is being used to press the IPL on the pins. The angular arrangement of the needles permits a form fit in addition to the friction effect between the needle's lateral surface and the IPL. To compensate elevations and inclinations, the guiding body is slightly tiltable. In addition, the needle spreading module protrudes somewhat from the MA due to the acting spring force. This also contributes, to a limited extent, to compensating dimples and uneven surfaces, besides the different extensions of the needles.

5.3. Design concept 3: Moving needles vertical into IPL

To be able to dispense with the kinematics of a separate attachment or the necessary step of fixation after placing the MA on the IPL, which would be associated with a separate attachment, the design concept 2 was modified resulting in a needle plate, see Fig. 8.

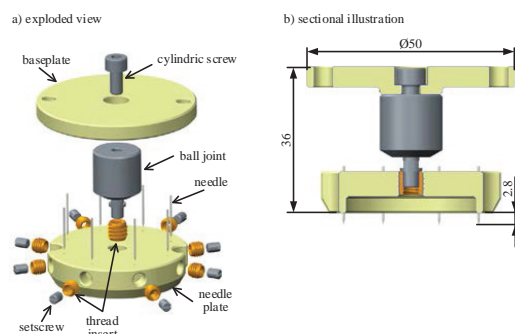


Fig. 8. Flexible attaching module based on needles that stand out perpendicular to the needle plate.

The perpendicular extension of the needles fixes the MA directly on the IPL as a holding force is generated simultaneously with the penetration of the needles into the IPL. An integrated ball joint permits spatial flexibility.

5.4. Design concept 4⁴: Pressing a film over the laminating attachment and the IPL

A common process for manufacturing CFRP panels is vacuum bag moulding by which the laminating setup is enclosed by a film and then evacuated. In this process, the laminate is pressed down on the mould and the entire laminating setup is fixed during the subsequent laminate hardening process. [9]

Fixing the MA can be done in a similar way. After it has been positioned on the IPL, a film is placed over both to seal the entire system, see Fig. 9.

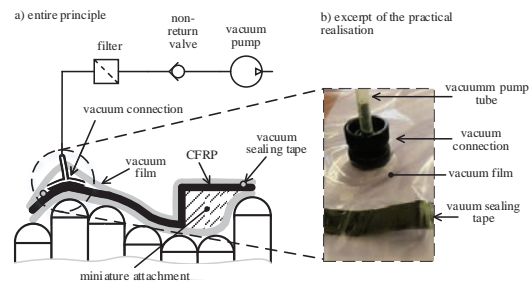


Fig. 9. Attaching principle based on pressing a film over a laminating attachment and an IPL.

6. Experimental procedure to compare each design concept's assembly strength

6.1. Experimental set-up

A set-up was designed and the experiments were performed to compare the described attachment concepts with regard to their assembly strength. Required elements are the laminating attachment's (LA) *test body* which is to be *attached* under different *IPL conditions*.

Test body. The exemplary LA's test body was loaded in three different directions by pulling force, applied via metallic thread insert and eyebolt, see Fig. 10a.

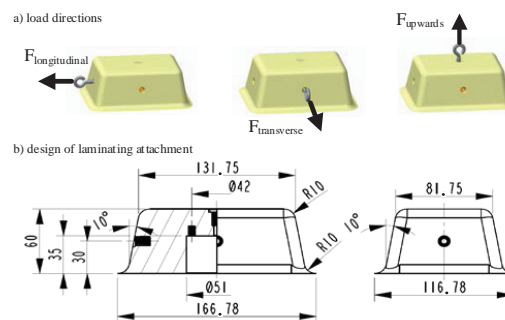


Fig. 10. Laminating attachment with directions of force load (a) and design illustration with nominal dimension in mm (b).

Attachment. The attaching design concepts (see chapter 5) were assembled one after the other into an assembly space as a material section (\varnothing 51 mm, 35 mm) within the LA, see Fig. 10b. The assembly occurred by screwing via thread inserts (\varnothing 42 mm, 35 mm).

IPL conditions. The following IPL conditions, which typically arise from the use of pin-type mouldings, were subjected to the experiment, see Fig. 11: a flat and not dimpled, versus a flat and dimpled, versus a spatially curved and not dimpled, versus a spatially curved and dimpled IPL. This results in four test series meaning that each module was tested under these four different IPL conditions.

⁴ Not shown in Fig. 5, since not using a module like in design concepts 1, 2, and 3.

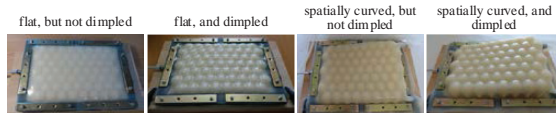


Fig. 11. Four typical IPL conditions, arising from pin-type moulding, represented by the realised experiment base.

To achieve those four IPL conditions, two experiment bases were used: one flat and one spatially curved. Both represent two exemplary settings of a pin-type mould (width = 228.0 mm, depth = 160.0 mm, number of pins = $4 \times 8 + 3 \times 9 = 59$, equal diameter of each pin = 27.7 mm). On both experiment bases, an IPL (silicone plate, thickness = 3 mm, 60 ± 5 Shore A, tensile strength ≈ 5 MPa, elongation at break $\approx 350\%$) was placed and sealed by a vacuum tape sealing and by compression via screwing steel plates at the borders, see Fig. 11. The dimpling effect was created by integrating small holes between the pins within the experiment base. These holes join in a channel-like system underneath the pins, which, in turn, joins into a single channel connected to a vacuum pump, see Fig. 12. Thus, after applying a vacuum, the interpolation layer is pressed on the pins and the dimples occur. The spatially curved experiment base was created by lifting each pin to a different height.

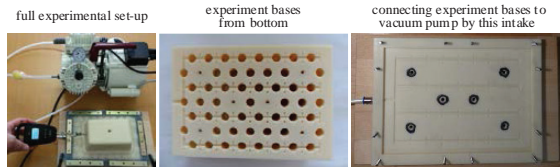


Fig. 12. Channel-like system in order to generate dimples via vacuum.

6.2. Results

In the following Fig. 13 ... 16, the releasing force required in each of the four different IPL conditions are summarised and compared to each other for the five attaching principles investigated within this article. In the two design principles using needles, the prick depth was fixed at 2.8 mm. The dimpling effect was reached by applying a vacuum of approximately 90%.

As the results indicate, in each case, design concept 4 (pressing a film, which was in this investigation the following: polyolefin copolymer, thickness = 80 μm , elongation at break $\approx 1000\%$, weight = 74 g/m^2) required by far the highest releasing force; however, the value of 192.3 N was the display range limit of the measuring device used for this experiment and the MA could not be released even at this value. Design concept 1 failed fully on the dimpled IPL, since the dimples cannot be fully compensated by the elasticity of the materials used for the suction cup and the bellows suction pad. But, in the case of a not dimpled IPL, design concept 1 was applicable and the suction cup was even the best with respect to upwards pull, after the pressing film.

Although pressing a film results in the best principle with respect to the releasing force, this kind of MA is not useful: as it turned out while experimenting, undesired wrinkles are

formed within the film which would be mapped onto the CFRP surface. Furthermore, dimpling is state of the art for today's pin-type moulds with a thin, elastic IPL and upwards pulling does not occur as a rule during manual lamination of CFRP. The experiments showed the suction cup and the bellows suction pad had poorer results than the designs based on needles with respect to longitudinal and transversal releasing force.

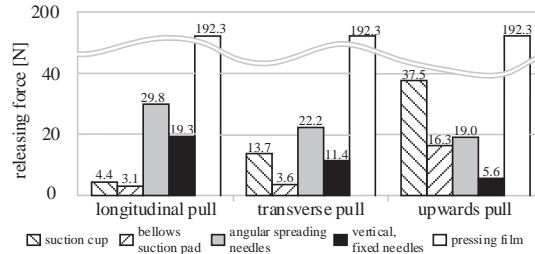


Fig. 13. Releasing force in the case of a flat and not dimpled IPL.

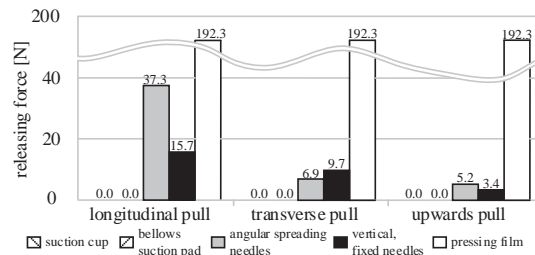


Fig. 14. Releasing force in the case of a flat and dimpled IPL.

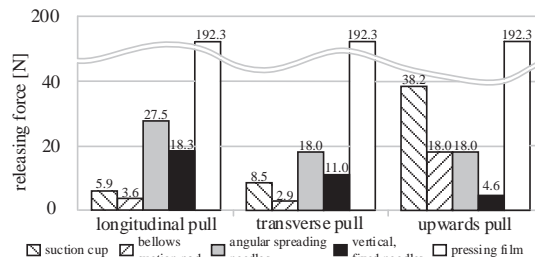


Fig. 15. Releasing force in the case of an uneven and not dimpled IPL.

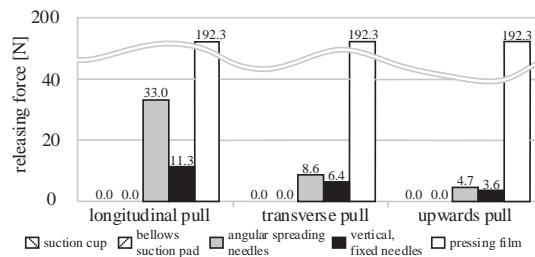


Fig. 16. Releasing force in the case of an uneven and dimpled IPL.

In the following Fig. 17 ... 20, both design principles based on needles were investigated with respect to different prick

depths. In both cases the releasing force increased with increase in the depth of needle prick into the IPL. Furthermore, in both cases the spreading needles are more powerful than the needle plate, except in the low range of prick depth on the flat and dimpled IPL, as indicated in Fig. 18. In the case of the dimpled IPL, the spreading needles amplify their releasing force to a greater extent than the needle plate with an increase in prick depth.

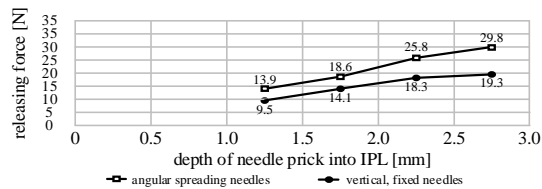


Fig. 17. Releasing force of needle spreader versus needle plate with different depths of prick in the flat and not dimpled IPL.

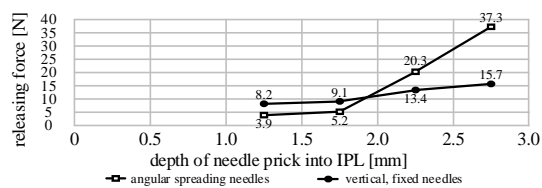


Fig. 18. Releasing force of needle spreader versus needle plate with different depths of prick in the flat and dimpled IPL.

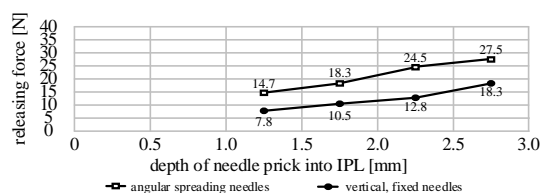


Fig. 19. Releasing force of needle spreader versus needle plate with different depths of prick in the uneven and not dimpled IPL.

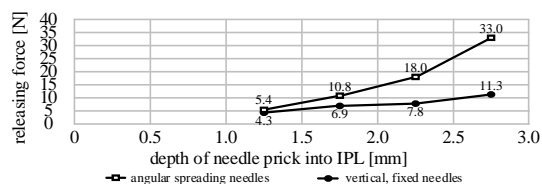


Fig. 20. Releasing force of needle spreader versus needle plate with different depth of prick in the uneven and dimpled IPL.

7. Summary and future work

This article presents the necessity for developing adequate attaching concepts for laminating attachments in order to increase the design freedom within pin-type moulding, spatially curved CFRP panels. Several design concepts were

introduced and compared to each other via experimental series. Since not only design solutions were determined but also their limits, future work is warranted.

The following ideas for design improvement for each introduced concept are potential areas for future work. Since the results for the attaching method by pressing a film were by far the best, but remain not applicable due to wrinkling, future investigation could focus on film materials with low tendency to wrinkle. Suction cup and bellows suction pad designs could possibly be developed for dimpled IPLs using more elastic material to better compensate larger variations in the contours of the dimpled surface. Both needle designs could be further developed and investigated with respect to, e.g., the influence of the number, angle arrangement, and position of the needles within the attachment module. Furthermore, the needles could be designed to be moveable independently of each other, in order to compensate spatially curved surfaces better.

In general, the design concepts could be developed and categorised with respect to existing design parameters of pin-type moulds for CFRP laminating, such as different IPL materials, thicker/thinner IPLs, larger/smaller pins and dimples, different pin geometries (e.g. triangle or squares), etc.

Finally, if the creative design process is continued, entirely new solutions are imaginable, such as: fixing by magnetic force flow to the pins if these have favourable magnetic properties, attaching via rasterised assembly insert positions within the IPL, adhesive joints, etc.

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